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The Collapsar Model for Gamma-Ray Bursts

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Abstract. We consider the relation among collapsars, supernovae, X-ray flashes, and other possible off-axis phenomena, e.g., uv-transients. New three-dimensional calculations are presented of relativistic jet propagation and break out in a massive Wolf-Rayet star. The supernovae that accompany GRBs are novel and need not be standard candles. Because of continuing energy input at late times, afterglows need not uniquely reflect either the opening angle or the energy of GRBs. The structure of the jet is neither a top hat nor a (single) Gaussian, and energy and Lorentz factor do not have the same angular dependence. We speculate on the existence of other forms of high energy transients at high redshift.

INTRODUCTION

It is now generally acknowledged that "long-soft" gamma-ray bursts (GRBs) are a phenomenon associated with the deaths of massive stars. At least one burst was accompanied by a nearly simultaneous supernova, SN 2003dh [1, 2], which had an unusual spectrum, copious radio emission, and showed evidence of asymmetric expansion [3]. Bumps in the afterglows of other GRBs, the association of GRB counterparts with regions of active star formation, and growing evidence linking SN 1998bw with GRB 980425, all strongly suggest that SN 2003dh was not exceptional - that many, if not all GRBs have supernova counterparts.[1] This narrows the model space considerably, leaving only theories in which the compact object formed by iron core-collapse is able to energize a relativistic jet. The remaining viable candidates are the millisecond magnetar [4, 5] and the collapsar [6, 7]. We explore here some implications of the collapsar model and some generic predictions associated with relativistic shock break out in a star.

SUPERNOVAE

The supernova produced in the collapsar model is novel in several regards. First, it is aspherical with very high velocities along the polar axis and low velocities in the equatorial plane. Relativistic matter is ejected in varying amounts and energies in a supernova whose total (mostly non-relativistic) kinetic energy is more or less constant. Relativistic flow is channeled along the rotational axis, *but this relativistic jet is not*

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[1] The converse is not true Most supernovae do not have GRB counterparts. Only about 1% do.

responsible for most of the explosion energy. The jet subtends too small a solid angle and the lateral shock it launches is not that powerful. Most of the energy for the supernova comes from the disk wind [7]. Nucleons flowing off of the accretion disk recombine into iron-group nuclei, and it is this kinetic energy that is responsible for the $\gtrsim 10^{52}$ erg of the explosion. Observations of GRB energies [8] and supernova energies [9, 10, 3] suggest that the energy from this wind - and therefore in the supernova - exceeds by as much as 10, the energy of the GRB-producing jet.

Second, since the ^{56}Ni is made by the wind and not by a spherical shock, its mass is not so limited by shock wave hydrodynamics. Producing 0.5 $M_{\odot}$ is not so difficult. Naively, one expects that the ^{56}Ni mass will be some fraction of the total mass accreted by the black hole and (naively squared) that the total energy of the GRB will be proportional to this same mass, i.e., brighter, longer GRBs will make brighter supernovae. [2] This simple expectation can be complicated however by electron capture in the disk [11] and by variable efficiency factors relating the GRB luminosity to the accreted mass. There is no clear reason for the supernovae that accompany GRBs to be standard candles, though they might be so, to a factor of several, because the accreted mass is always similar.

Finally, a collapsar continues to provide energy from fallback and accretion a long time after the main burst is over [12]. As the star explodes, the opening angle of the jet increases. The total energy at late times (minutes to a day) could even be greater than the GRB energy. This possibility should be kept in mind when limiting the energies and angles of GRBs by "breaks" in their afterglows observed days after the event [8, 13].

XRFs AND UVFs FOLLOWING JET BREAKOUT

Zhang, Woosley, & Heger [14] recently studied jet break out in collapsars in 2D and 3D. Figs. 1 and 2, from that paper, show some relevant properties of a typical jet as it emerges. The part that makes the GRB, about 3 - 4 degrees in radius with $\Gamma \sim 200$, is surrounded by a lower energy cocoon [15] of "mildly" relativistic material, with Γ up to 20 - 40, which explodes to larger angles. The interaction of this off-axis material with the circumstellar wind of the star seems certain to give rise to high energy transients of some sort. Predicting their properties from first principles is difficult though, because of uncertainty in the emission mechanism and efficiency factors. In contrast to the modulated Lorentz factor found in the central core of the jet, the calculations do not show significant non-monotonic variation in velocity with radius for the off-axis component. External shocks might therefore dominate (though see [21] for a "shock-less" internal magnetic dissipation model). Dermer, Chiang, & Böttcher [17] suggested a "dirty fireball"of this sort might produce softer transients. The peak photon energy in the external shock model depends on $n^{1/2}\Gamma^4$ [18], but for reasonable values of $\Gamma \sim 30$ and $n \sim 10^5 r_{15}^{-2}$ cm^{-3}, could be in the keV range. There would be multiple values of Γ in the observer's line of sight, so the spectrum would not be sharply peaked. As in past papers [19, 20, 16, 14], we associate these lower power, possibly softer emissions

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[2] The brightness, at peak, of a Type I supernova of any subclass is directly proportional to the mass of ^{56}Ni it ejects. This is known as "Arnett's Rule"

with x-ray flashes (XRFs, [22]). Recently several groups [23, 24, 25] have have determined a relation between peak photon energy and GRB equivalent isotropic energy, $E_{\rm peak} \sim 100\ (E_{\rm iso}/10^{52}\ {\rm erg})^{1/2}$ keV, that fits both GRBs and XRFs. While the core emission in Fig. 2 is close to 10^{54} erg, this is the kinetic energy. The radiative $E_{\rm iso}$ would be less, by perhaps 10, implying a photon energy in the core of $\sim$ 300 keV. In the wings, the scaling relationship would imply peak energies about 10 times less, i.e., hard x-rays. Still softer emission could come from the wings farther out.

If this picture is true, then every GRB is also an X-ray flasher and every GRB light curve will contain, sometimes at a very low level, an XRF coming from the wings of the jet. Given the different emission mechanisms (internal *vs.* external shocks) and efficiency factors (external shocks are thought to be more efficient), the ratio of the brightnesses is unknown. XRFs could be a large fraction of the observed high energy transient event rate and they are certainly more numerous than GRBs (because of the large angle to which they are visible).

If XRFs are made this way,[3] several predictions emerge. First, since every XRB is just a GRB seen at a different angle, XRFs should share the spatial distribution of GRBs. They should also be accompanied by a supernova (though not necessarily a standard candle). Because they are visible to a larger angle, more XRFs are potentially detectable than GRBs, but because they are less powerful, they are sampled to a shorter distance. It may be that the log N - log S distribution for XRFs will not roll over in the same way as GRBs. We may not have seen to the edge of the distribution yet (hence a more sensitive detector would see a rise in the ratio of XRFs to GRBs).

But why stop with XRFs? For somewhat lower Γ and larger angles, the peak emission could fall into the ultraviolet or even optical range. Then one expects GRBs in the jet core, XRFs in the near wings, and UV flashes in the broad wings. *The most common observable transient produced by jet breakout may not be in gamma-rays or x-rays, but in the ultraviolet* [26]. This important conclusion may have implications for SWIFT.

The total energy in the wings of the jet is not large though. 90% of the relativistic ejecta ($\Gamma > 5$) are within 6 degrees of the axis (integral of Fig. 2). One does not expect this material at large polar angle to contribute appreciably to the afterglow - compared with the decelerated GRB jet itself. However, there may still be a lot of energy radiated at large angle and later times if the central black hole continues to accrete and power a jet after the principal GRB is over. Given the expected fallback in the collapsar, which could easily generate 10^{51} erg, this is likely.

OTHER PREDICTIONS OF THE COLLAPSAR MODEL

This continuing emission could also have important implications for putative x-ray lines in GRBs. During the first day, most of the star is expelled as a supernova which remains

[3] An alternate possibility, hard to disprove at the present time, is that XRFs are the *on axis* emissions of collapsars that,for whatever reason, did not develop as high a Lorentz factor as in GRBs. This could reflect instabilities in the jet [14], a more extended progenitor, or simply a jet that, for whatever reason, never attained a very high energy per baryon.

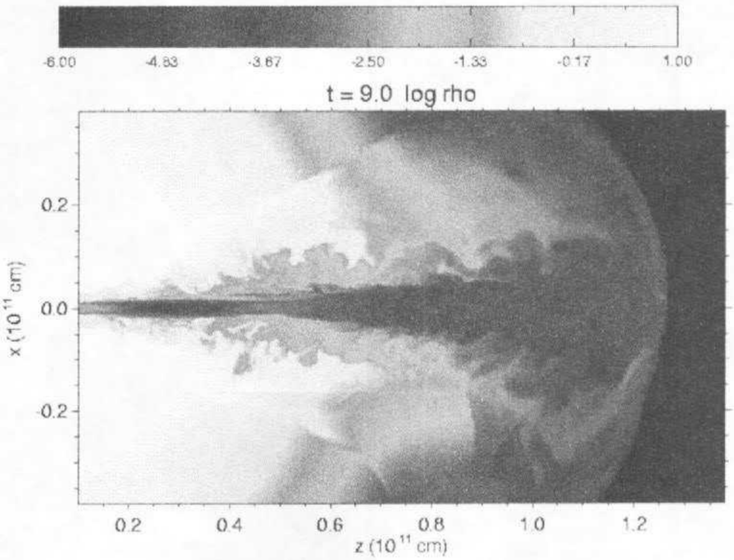

FIGURE 1. Jet breakout in Model 2A of ref. [14]

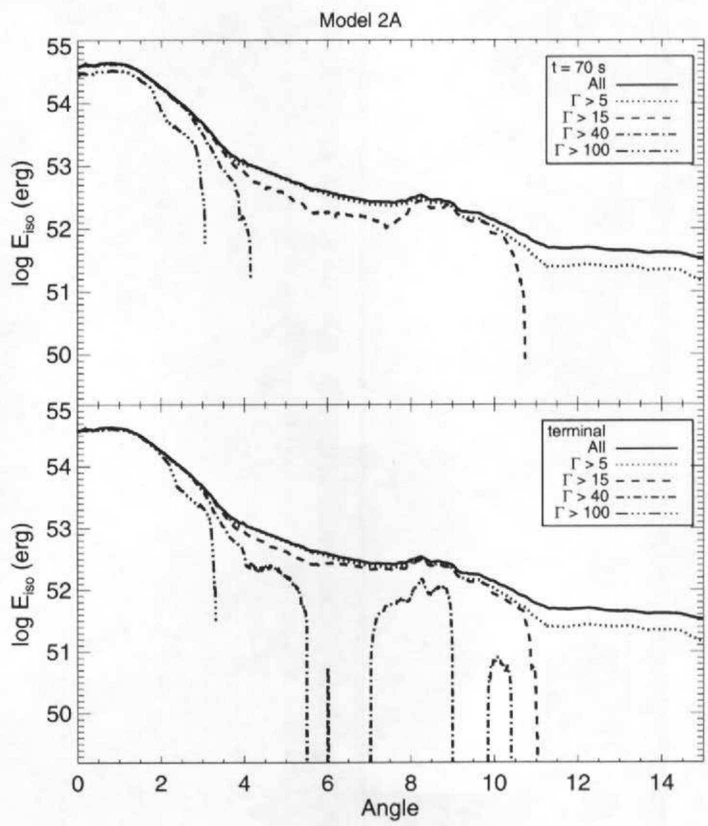

FIGURE 2. Distribution of Lorentz factor and equivalent isotropic energy in Fig. 1. It is assumed that all internal energy converts to kinetic in oredr to calculate a terminal Lorentz factor.

optically thick out to $\sim 10^{15}$ cm for weeks. However, along the polar axis, a jet continues to flow, energized by fallback from the supernova [12] which declines as roughly $t^{-5/3}$. After a day, the power may still be $\sim 10^{46}$ erg s^{-1} (for an accretion rate of 10^{-7} $M_\odot$ s^{-1} with efficiency 5% $\dot{M}c^2$). Internal shocks within this jet could irradiate the slower moving, subrelativistic material along the jet nozzle and make x-ray lines [27]. If this is the origin of the lines, they would be brightest when the star along the rotational axis first becomes optically thin and decline rapidly ($\sim t^{-5/3}$ thereafter).

The collapsar model also predicts that GRBs of duration less than hundreds of seconds will only originate from Type Ib/c supernovae, never from red or blue supergiants (BSGs). Our unpublished calculations show that a jet with typical power for a GRB, left on for 70 s in a blue supergiant (radius 3×10^{12} cm) only reaches 10^{12} cm and that the jet head is advancing subrelativisitically. If the power source at the origin is removed, the jet dissipates quickly, after encountering its rest mass. However, it is still possible that some sort of high energy transient, an XRF or UVF, could originate from a BSG [12]. A very long GRB is also a possibility. Given that most massive stars at high redshift are BSGs when they die, these sorts of transients could be common.

Indeed, at high redshift, several new varieties of high energy transients from collapsars could become visible. Type III collapsars occur when the pair instability leads to core collapse in a rotating star of several hundred solar masses [28]. These objects would produce very energetic transients lasting hundreds of seconds in the rest frame. It is difficult to estimate the jet energy and γ-ray efficiency in such hypothetical objects, but they could resemble ordinary GRBs in terms of Lorentz factor and peak photon energy. If so, one expects powerful bursts of hard x-ray emission from redshift ~ 15 lasting, perhaps, several hours. These would be a distinctive signature of the first stars to form after the "Dark Ages".

But why stop at 300 $M_\odot$? An enduring puzzle in astrophysics has been the origin of the supermassive black holes found in both active and normal galactic nuclei. There may not have been enough time to grow black holes of $\gtrsim 10^6$ $M_\odot$ from scratch before the first quasars are seen. One possibility (e.g.[29, 30]) is that they formed from supermassive stars, also of $\gtrsim 10^6$ $M_\odot$. If these stars rotated anywhere near break up, the new (Kerr) black hole would be surrounded by a disk with mass roughly 10% that of the hole [31]. [4]. The natural hydrodynamic time scale for such a collapse is about a day, and one might expect accretion from the disk to go on for that long [5]. Accretion of $\gtrsim 10^5$ $M_\odot$ in 10^5 s, assuming 1% conversion of the rest mass gives jets with power 10^{52} erg s^{-1} and total energy 10^{57} erg. These factors may be further amplified an additional factor of $\sim$100 by beaming. The Lorentz factor and photon energy is unknown, but the accretion rate is not unlike the most energetic GRBs. If emission were in the gamma-ray band, the redshift would give bursts in hard x-rays with GRB-line fluxes lasting several weeks. The greatest uncertainty is the event rate. Including beaming, estimates are in the range

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[4] We could call such an object a "Collapsar Type IV", the other three types being prompt black hole formation in a massive star [7], black hole formation by fallback [12], and black hole formation in a pair-instability collapse[28].

[5] Shibata & Shapiro [31] estimate a much longer time scale, but ignore cooling by neutrino emission or the disk wind.

a few per year to a few per century [32, 33]. While this is very uncertain, the good news is that a detection one or two would help determine a very interesting, uncertain number - the birth rate of supermassive black holes in our universe.

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